NextGen Optical Clock

Completed Technology Project (2015 - 2018)

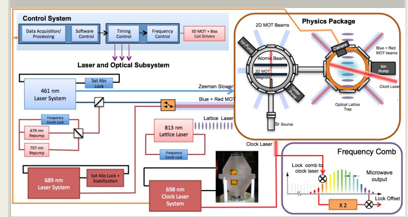
Project Introduction

The overall goal of this project is to establish optical lattice clock capability at JPL and to develop a critical path to a flight clock instrument for upcoming fundamental physics opportunities by developing and demonstrating a lattice optical clock prototype, performing at the 10^-16 level precision or better. It was recognized in the 2011 NRC Decadal Survey on Biological and Physical Sciences in Space that the potential of these clocks for fundamental science, in particular, has reached a critical level for unprecedented measurements of the gravitational redshift, variations of fundamental constants, Lorentz violations, gravitational wave detection, and relativistic geodesy to name a few. Building on the state-of-the-art laboratory lattice clock design at JILA/NIST, which demonstrated record stability and accuracy (at the 10^-18 level) during the PI’s tenure as a NIST/NRC postdoc on that project, and the expertise and capability at JPL for developing space-qualified atomic sensors/facilities for fundamental physics (e.g., the Cold Atom Laboratory), we anticipate to quickly take the lead in developing space-qualified optical clocks.

Optical atomic clocks are widely accepted as a revolutionary advancement in the evolution of atomic frequency standards. The maturity of these clocks, which operate at optical frequencies for higher quality-factor as compared to their microwave counterparts, has rapidly progressed to the point where numerous lab-based systems now outperform the best cesium clocks by orders of magnitude in both accuracy and stability. For comparison, an optical clock (OC) designed at JPL, with performance at the level of 10^-18 in fractional frequency units, will outperform the highest-precision cesium clock in space (ACES scheduled for launch to the ISS in 2017) by nominally two orders of magnitude with similar size and weight requirements. The target performance of the OC is extrapolated from that demonstrated in laboratory lattice clocks at JILA/NIST.

The key to utilizing the exceptional performance demonstrated by the optical lattice clocks in space now requires engineering development to extend from the laboratory designs to space-qualified instrument that can fit with the space and power constraints of e.g. the ISS. With the exception of ESA Space Optical Clock, there has been virtually no effort in developing optical clocks for space applications. Based on the expertise and capabilities at JPL for developing space-qualified atomic sensors/facilities for fundamental physics (e.g., the Cold Atom Lab), we anticipate to quickly take the lead developing space-qualified optical clocks during the R&TD project.

Five key components will be developed in this task: 1) Cooling and trapping the atoms in dual-stage (“Blue” and “Red”) MOTs to achieve high density in the “ultracold” regime. 2) An optical lattice to confine the atoms and remove broadening and shifts associated with the photon recoil, Doppler, and AC Stark effects. 3) The ultra-stable clock laser, with line width at or below the Hz level. 4) State-detection and feedback to stabilize the clock-laser, and 5) Time transfer of the clock signal to the microwave domain using an optical frequency comb.



Schematic of the prototype optical atomic clock. The atomic physics package includes a low-power strontium oven, a novel 2D MOT design, and a large-optical-access chamber for laser cooling and interrogation of the atoms.

Table of Contents

Many of the critical parts for the first and second components are commercially available and relatively technically mature, including the diode lasers and ultra-high vacuum hardware at the heart of the high-flux atom source. We will innovate in developing the laser systems, electromagnets, control electronics, and the physics package in a compact and rugged design. Components 3 and 4 will require significant innovation to develop compact and low-power breadboard subsystems designed to reduce the risk of extending the high-stability and performance of their lab-based counterparts for future flight designs. The self-referenced optical frequency comb, central to component 5, is available at our facility; independent projects ongoing at JPL are dedicated to miniaturizing the combs for this and similar space applications. These innovations will be natural and necessary to develop beyond the state of the art to mature the optical clocks for applications of interest to JPL and NASA.

No JPL effort, except the compact Yb+ optical clock, will have significant overlap with the innovations of this R&TD. The Yb+ clock, which is developed as part of the U.S. PI collaboration on the ESA Space Optical Clock project, is limited to tabletop investigations with the objective of compactness rather than high-performance. In contrast, the optical clock developed by this R&TD effort will aim toward extending the state of the art for precision timekeeping in space by at-least two orders of magnitude.

Anticipated Benefits

This project will mature the technology of stabilized laser systems and lead to space qualified ultra-stable lasers for potential follow-on missions to the Cold Atom Lab for studying fundamental physics on the International Space Station.

Establishment of an optical frequency standard at JPL is necessary to mitigate the technical risks in future developments of optical-clock-based missions. At the end of the three-year R&TD task, we anticipate that the prototype clock will be sufficiently advanced to enable the development of a next-generation optical clock payload e.g., onboard the ISS. Recent mission opportunities that have included fundamental physics and would have been directly addressable with optical-clock-based science include the SMEX call and the ESA Cosmic vision. Opportunities in the near-term are also anticipated e.g., to improve general relativity tests by several orders of magnitude, which has been specifically mentioned in NASA's Science plan for the Science Missions directorate as a high priority. Already, NASA is collaborating with ESA on the "Space Optical Clocks" project to develop the technology and to make the ultra-stable oscillator available for the International Space Station and next-generation GPS/navigation satellites, and there is interest at NASA HQ for starting up a space optical clock program. The availability of optical clocks for precision timekeeping and clock-synchronization will also have a profound impact to DSN, with orders of magnitude projected enhancement in spacecraft tracking and navigation, and enabling capabilities e.g., one-way navigations.

Organizational Responsibility

Responsible Mission Directorate:

Mission Support Directorate (MSD)

Lead Center / Facility:

Jet Propulsion Laboratory (JPL)

Responsible Program:

Center Independent Research & Development: JPL IRAD

Project Management

Program Manager:

Fred Y Hadaegh

Project Manager:

Fred Y Hadaegh

Principal Investigator:

Jason Williams

Co-Investigators:

Sheng-wey Chiow
Nan Yu

Center Independent Research & Development: JPL IRAD

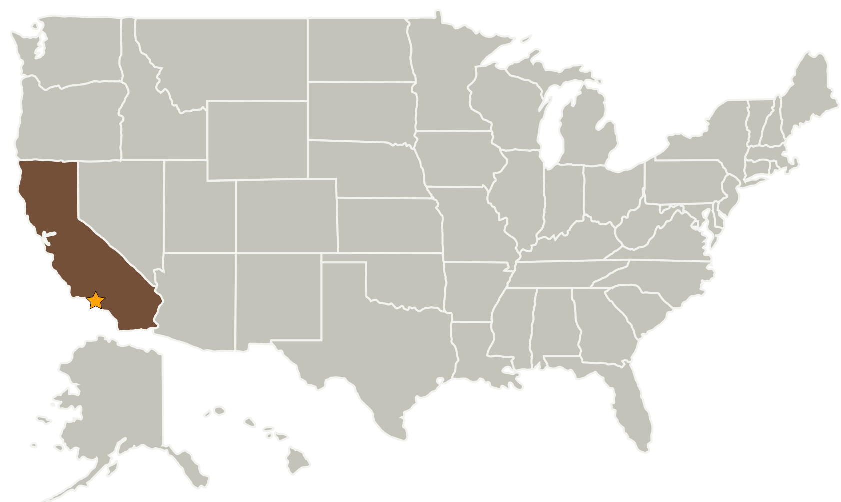
NextGen Optical Clock

Completed Technology Project (2015 - 2018)

Development of an optical frequency standard at JPL will provide a base sysytem for mitigating the technical risks in future developments of optical-clock-based mission concepts. These activities will, in turn, lead to collaborations that will mature the technology for near-term integration useful for commercial space industries.

The Department of Defense (DoD) is one of the heavy precision clock customers with ever increasing need for better clocks. They are largely driven by the need for jamming resistant GPS navigation and communications. The DoD also needs high performance clocks for space-based imaging. More recently, DARPA had several clock programs with BAA calls with tens of million dollar awards. It has recently indicated interests in optical clocks and related technologies and is in the process of formulating an optical clock program. Other DoD agencies, such as AFOSR, ONR, and NRO had funded clock programs in the past. Other government agencies, such as FAA, are also interested in advanced clocks. In fact, FAA has indicated their interest in investing in precision clock technology. It's safe to say that there are great interests and many business opportunities out there for clocks that are better than what we have today.

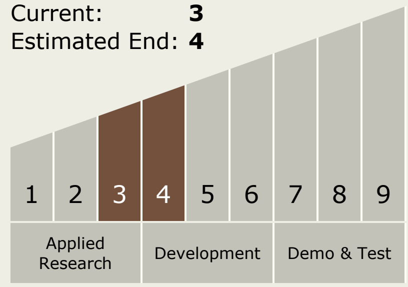
Primary U.S. Work Locations and Key Partners



Organizations Performing Work	Role	Type	Location
★Jet Propulsion Laboratory(JPL)	Lead Organization	NASA Center	Pasadena, California

Technology Maturity (TRL)

Start: **3**
Current: **3**
Estimated End: **4**



Technology Areas

Primary:

- TX05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
  └ TX05.4 Network Provided Position, Navigation, and Timing
    └ TX05.4.1 Timekeeping and Time Distribution

Target Destinations

Earth, Foundational Knowledge

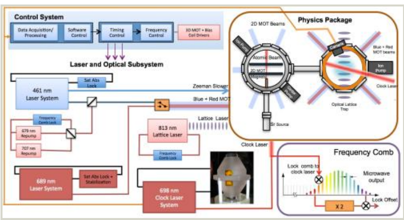
Supported Mission Type

Push

Primary U.S. Work Locations

California

Images



NextGen Optical Clock Image
Schematic of the prototype optical atomic clock. The atomic physics package includes a low-power strontium oven, a novel 2D MOT design, and a large-optical-access chamber for laser cooling and interrogation of the atoms.
(https://techport.nasa.gov/image/24469)